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Appendix I

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THE Electrical Engineering HANDBOOK

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28

Active Filters

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28.1 Synthesis of Low-Pass Forms

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Passive and Active Filters

There are formal definitions of activity and passivity in electronics, but it is sufficient to observe that passive filters are built from passive components; resistors, capacitors, and inductors are the commonly encountered building blocks although distributed RC components, quartz crystals, and surface acoustic wave devices are used in filters working in the high-megahertz regions. **Active filters** also use resistors and capacitors, but the inductors are replaced by active devices capable of producing power gain. These devices can range from single transistors to integrated circuit (IC) -controlled sources such as the operational amplifier (op amp), and more exotic devices, such as the operational transconductance amplifier (OTA), the generalized impedance converter (GIC), and the frequency-dependent negative resistor (FDNR).

The theory of filter synthesis, whether active or passive, involves the determination of a suitable circuit topology and the computation of the circuit component values within the topology, such that a required network response is obtained. This response is most commonly a voltage transfer function (VTF) specified in the frequency domain. Circuit analysis will allow the performance of a filter to be evaluated, and this can be done by obtaining the VTF, $H(s)$, which is, in general, a rational function of s, the complex frequency variable. The *poles* of a VTF correspond to the roots of its denominator polynomial. It was established early in the history of filter theory that a network capable of yielding complex-conjugate transfer function (TF) pole-pairs is required to achieve high selectivity. A highly selective network is one that gives a rapid transition between passband and stopband regions of the frequency response. Figure 28.1(a) gives an example of a passive low-pass LCR ladder network capable of producing a VTF with the necessary pole pattern.

The network of Fig. 28.1(a) yields a VTF of the form

$$H(s) = \frac{V_{\text{out}}(s)}{V_{\text{in}}(s)} = \frac{1}{a_5 s^5 + a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0} \qquad (28.1)$$

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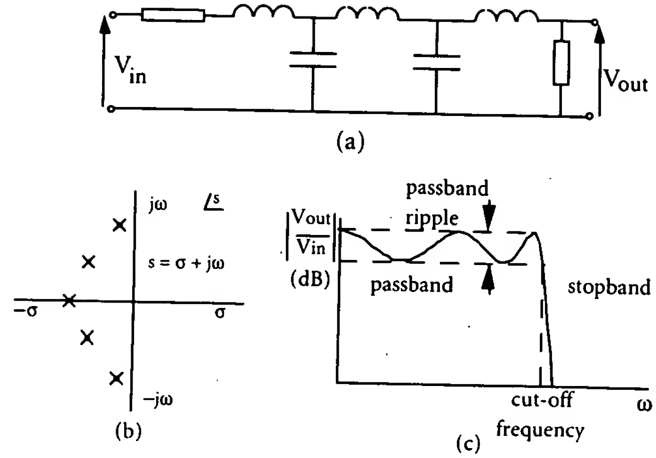

FIGURE 28.1 (a) Passive LCR filter; (b) typical pole plot; (c) typical frequency response.

Figure 28.1(b) shows a typical pole plot for the fifth-order VTF produced by this circuit. Figure 28.1(c) gives a sample sinusoidal steady-state frequency response plot. The frequency response is found by setting $s = j\omega$ in Eq. (28.1) and taking $|H(j\omega)|$. The LCR low-pass ladder structure of Fig. 28.1(a) can be altered to higher or lower order simply by adding or subtracting reactances, preserving the series-inductor/shunt-capacitor pattern. In general terms, the higher the filter order, the greater the selectivity.

This simple circuit structure is associated with a well-established design theory and might appear the perfect solution to the filter synthesis problem. Unfortunately, the problems introduced by the use of the inductor as a circuit component proved a serious difficulty from the outset. Inductors are intrinsically nonideal components, and the lower the frequency range of operation, the greater these problems become. Problems include significant series resistance associated with the physical structure of the inductor as a coil of wire, its ability to couple by electromagnetic induction into fields emanating from external components and sources and from other inductors within the filter, its physical size, and potential mechanical instability. Added to these problems is the fact that the inductor tends not to be an off-the-shelf component but has instead to be fabricated to the required value as a bespoke device. These serious practical difficulties created an early pressure to develop alternative approaches to electrical filtering. After the emergence of the electronic amplifier based on thermionic valves, it was discovered that networks involving resistors, capacitors, and amplifiers—*RC-active filters*—were capable of producing TFs exactly equivalent to those of LCR ladders. Figure 28.2 shows a single-amplifier multiloop ladder structure that can produce a fifth-order response identical to that of the circuit of Fig. 28.1(a).

The early active filters, based as they were on valve amplifiers, did not constitute any significant advance over their passive counterparts. It required the advent of solid-state active devices to make the RC-active filter a viable alternative. Over the subsequent three decades, active filter theory has developed to an advanced state, and this development continues as new IC technologies create opportunities for novel network structures and applications.

Active Filter Classification and Sensitivity

There are two major approaches to the synthesis of RC-active filters. In the first approach, a TF specification is factored into a product of second-order terms. Each of these terms is realized by a separate RC-active subnetwork designed to allow for non-interactive interconnection. The subnet-

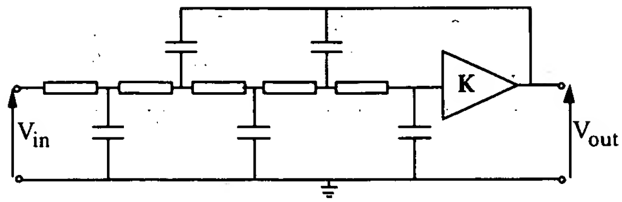

FIGURE 28.2 RC-active filter equivalent to circuit of Fig. 28.1(a).

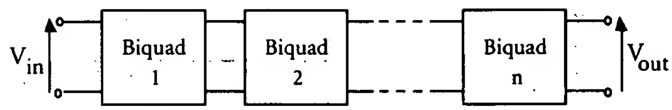

FIGURE 28.3 Biquad cascade realizing high-order filter.

works are then connected in cascade to realize the required overall TF, as shown in Fig. 28.3. A first-order section is also required to realize odd-order TF specifications. These second-order sections may, depending on the exact form of the overall TF specification, be required to realize numerator terms of up to second order. An RC-active network capable of realizing a biquadratic TF (that is, one whose numerator *and* denominator polynomials are second-order) is called a **biquad.**

This scheme has the advantage of design ease since simple equations can be derived relating the components of each section to the coefficients of each factor in the VTF. Also, each biquad can be independently adjusted relatively easily to give the correct performance. Because of these important practical merits, a large number of alternative biquad structures have been proposed, and the newcomer may easily find the choice overwhelming.

The second approach to active filter synthesis involves the use of RC-active circuits to simulate passive LCR ladders. This has two important advantages. First, the design process can be very straightforward: the wealth of design data published for passive ladder filters (see Further Information) can be used directly so that the sometimes difficult process of component value synthesis from specification is eliminated. Second, the LCR ladder offers optimal **sensitivity** properties [Orchard, 1966], and RC-active filters designed by ladder simulation share the same low sensitivity features. Chapter 4 of Bowron and Stephenson [1979] gives an excellent introduction to the formal treatment of circuit sensitivity.

Sensitivity plays a vital role in the characterization of RC-active filters. It provides a measure of the extent to which a change in the value of any given component affects the response of the filter. High sensitivity in an RC-active filter should also alert the designer to the possibility of oscillation. A nominally stable design will be unstable in practical realization if sensitivities are such that component value errors cause one or more pairs of poles to migrate into the RHP. Because any practical filter will be built with components that are not exactly nominal in value, sensitivity information provides a practical and useful indication of how different filter structures will react and provides a basis for comparison.

Cascaded Second-Order Sections

This section will introduce the cascade approach to active filter design. As noted earlier, there are a great many second-order RC-active sections to choose from, and the present treatment aims only to convey some of the main ideas involved in this strategy. The references provided at the end of this section point the reader to several comprehensive treatments of the subject.

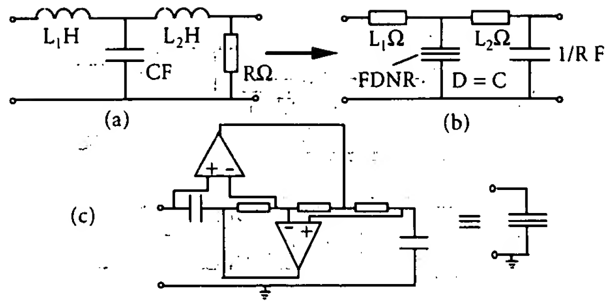

FIGURE 28.11 FDNR active filter.

large so that, again, there is a chip-area problem. The solution to this dilemma emerged in the late 1970s/early 1980s with the advent of the switched-capacitor (SC) active filter. This device, a development of the active-RC filter that is specifically intended for use in IC form, replaces prototype circuit resistors with arrangements of switches and capacitors that can be shown to simulate resistances, under certain circumstances. The great merit of the scheme is that the values of the capacitors involved in this process of resistor simulation are inversely proportional to the values of the prototype resistors; thus, the final IC structure involves principal and switched capacitors that are small in magnitude and hence ideal for IC realization. A good account of SC filters is given, for example, in Schaumann *et al.* [1990]. Commonly encountered techniques for SC filter design are based on the two major design styles (biquads and ladder simulation) that have been introduced in this section.

Many commercial IC active filters are based on SC techniques, and it is also becoming usual to find custom and semicustom IC design systems that include active filter modules as components within a macrocell library that the system-level design can simply invoke where analog filtering is required within an all-analog or mixed-signal analog/digital system.

Defining Terms

Active filter: An electronic filter whose design includes one or more active devices.

Biquad: An active filter whose transfer function comprises a ratio of second-order numerator and denominator polynomials in the frequency variable.

Electronic filter: An electronic circuit designed to transmit some range of signal frequencies while rejecting others. Phase and time-domain specifications may also occur.

Sensitivity: A measure of the extent to which a given circuit performance measure is affected by a given component within the circuit.

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